Evaluation of Stress of Austenitic Stainless Steel after Surface Processing by Means of an Eddy Current Method

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授　与　学　位	博士（工学）
学位授与年月日	平成24年3月27日
学位授与の根拠法規	学位規則第4条第1項
研究科，専攻の名称	東北大学大学院工学研究科（博士課程）ナノメカニクス専攻
学位論文題目	Evaluation of Stress of Austenitic Stainless Steel after Surface Processing by Means of an Eddy Current Method （表面加工したオーステナイト系ステンレス鋼の応力の渦電流法による評価）
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論　文　内　容　要　旨

Chapter 1　Introduction

To establish a safe society, it is important to enhance reliability of mechanical structures and components. To do this, improvement of fatigue properties should be required. Fatigue strength of metallic materials is affected by residual stress and stress state. Because variation of bending stress is largest at the surface when fatigue occurs, initiating point of the fatigue crack is the surface in general. Thus, to enhance the fatigue strength, introduction of compressive residual stress at the surface is effective. The residual stress relates the fatigue life, and the stress state relates propagating direction of cracks. To enhance the fatigue strength of metallic materials, peening and surface finishing techniques are conducted to introduce the compressive residual stress and to change the stress state. Not only the fatigue strength but also stress corrosion cracking (SCC) resistance is improved by these surface processing techniques. To establish the safe society, it is also required that SCC should be prevented. When the compressive stress is introduced, the SCC resistance is improved. From the points of the fatigue strength and the SCC resistance, the stress states role important factors. In addition, surface modified thickness where the compressive stress is induced is important to control the SCC resistance. To confirm the stress state of materials in service and practical use, nondestructive stress evaluating method should be established. The nondestructive method enables to use the inspected materials continuously.

There are various evaluating methods of the stress state. In the points that it takes brief time to evaluate the stress state at the surface and it is easier method, the electromagnetic methods are proper to evaluate stress state nondestructively, because penetration depth can be varied with measuring frequency, testing time is shorter than those of any other methods, controlled area is not required, and electromagnetic properties are varied with stress. The electrical resistivity varies with stress due to variation of potential energy of atomic elements. The magnetic permeability varies with stress due to variation of magnetization in ferromagnetic materials. In particular, an eddy current method can be applied for not only paramagnetic materials but also ferromagnetic materials. In this thesis, to establish an evaluating method of stress state at the surface of austenitic stainless steel, an eddy current method is focused. Austenitic stainless steel is used for tanks and tubes in atomic power plants. Various surface processing techniques like as peening are conducted for austenitic stainless steel to prevent SCC. Thus, nondestructive stress evaluating method for the austenitic stainless steel after surface processing in brief time is important. To consider the SCC resistance, Japanese Industrial Standards (JIS) SUS316L, which is hard to occur deformation-induced martensitic transformation, was tested. In addition, cavitation peening (CP), which occurs small increase of surface roughness and small variation of microstructural change, is focused in this study. It can be described that the main reason of electromagnetic properties change by CP is introduction of the compressive residual stress. The compressive stress introduced by CP is almost proportional to the depth from the surface.

In previous studies, eddy current signal variations of uniaxial stress state are investigated. However, biaxial stress state must be varied after peening or surface processing. In particular, equibiaxial compressive stress is induced by general peening methods. Thus, to evaluate the peening intensity like as the introduction of compressive equibiaxial stress by an eddy current method, eddy current signal variation with equibiaxial compressive stress should be investigated. The eddy current signal is affected by electromagnetic properties at certain depth due to the skin effect. To use this phenomenon, the peened thickness where the equibiaxial compressive stress is introduced can be evaluated. To evaluate the peened thickness which is related to the SCC resistance, the variation of electromagnetic properties with the depth should be determined from the eddy current signal. To do the determination, an inverse analysis is required. In this thesis, the inverse analysis method using a response surface is induced to determine the peened thickness by CP. To conduct the response surface methodology for the inverse analysis, precise thickness determination can be conducted because eddy current signals at all frequency can be used for the determination of the peened thickness comprehensively. To establish the stress measuring system with an eddy current method, stress anisotropy should be evaluated because stress anisotropy decides propagating direction of cracks. To evaluate the stress anisotropy with conventional techniques like as an X-ray diffraction method, it takes long time. To detect the stress anisotropy, flow direction of eddy current should be controlled. In this study, an eddy current method using a tangential-rectangular coil is focused to control the flow direction of eddy current and used for measurement of the shearing stress. In this thesis, the goal of the study was set to establish nondestructive evaluating methods using eddy current methods of real stress state of stainless steel after surface processing like as peening and grinding. The nondestructive evaluation should be containing to consider the depth distribution of residual stress. In this thesis, the stress evaluating method of SUS316L using an eddy current method considering the stress state of various directions was proposed. In addition, anisotropic stress state after grinding which can give stress anisotropy and peening was also evaluated by the eddy current method with the tangential-rectangular coil. The peening is conducted by CP considering little microstructural change and linear residual stress distribution with depth from the surface.

Chapter 2 Evaluation of Equibiaxial Compressive Stress Using an Eddy Current Method

In this chapter, to establish the stress evaluating method of peened austenitic stainless steel using an eddy current method, the variation of eddy current signal with compressive equibiaxial stress induced mechanically which is the same stress state after general peening methods was investigated. In result, the eddy current signals like as coil reactance vary with the peening processing time or the equibiaxial compressive stress induced mechanically. The stress distribution of CP specimen and that of the specimen induced equibiaxial compressive stress mechanically are different. Thus, the variation of the electrical resistivity of the CP specimen and that of the specimen induced equibiaxial compressive stress were calculated from the eddy current signals. The variation of resistivity of the peened specimen was assumed based on the stress distribution after peening obtained from a former report. Figure 2.21 shows the relationship between the resistivity at the surface normalized by that of the non-compressed value and the stress at the surface. From Fig. 2.21, the gradient of the equibiaxial specimen is 30 ± 20 TPa^{-1}, and that of the CP specimen is 50 ± 30 TPa^{-1}. Considering the reference value of the gradient, 24 TPa^{-1}, the calculated variation in the electrical resistivity by CP evaluated by the eddy current method is related to that of the equibiaxial compressive stress. The resistivity decreases with the induced compressive stress. Thus, it is possible to establish the method to evaluate the equibiaxial stress induced by peening using the eddy current signals.

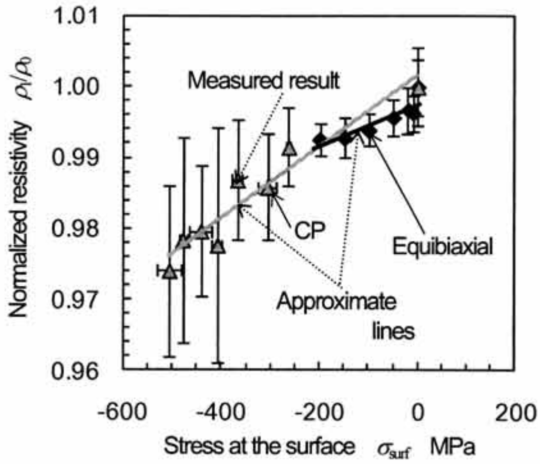

Fig. 2.21 Variation of the normalized resistivity with the stress at the surface at f = 400 kHz

Chapter 3 Evaluation of the Thickness of the Layer Modified by Cavitation Peening Using an Eddy Current Method with Inverse Analysis

In this chapter, to establish evaluating method of peening intensity, thickness of the surface modified layer by CP where compressive residual stress is introduced was determined using an eddy current method. The peened thickness affects property of resistance to SCC. The determination of the peened thickness can not be conducted only using eddy current signals. Thus, the inverse analysis was required and conducted. The inverse analysis conducted in this thesis is that the depth distribution of electrical resistivity was determined from the eddy current signals. To consider the electrical resistivity at the depth which is deeper than the penetration depth of the eddy current, the inverse analysis using a response surface methodology was conducted in this thesis. Figure 3.9 shows the relationship between measured thickness by an X-ray diffraction method and the estimated thickness determined by the eddy current method using the inverse analysis with the response surface methodology. From Fig 3.9, the gradient of the approximate line is 1.1 ± 0.3, and the probability of that there is no correlation among those two thicknesses is 9.8 %. From these results, the determined modified thickness agrees with measured thickness. Thus, the eddy current method can evaluate the peened thickness, and it is possible to establish evaluating method of the peening intensity using the method.

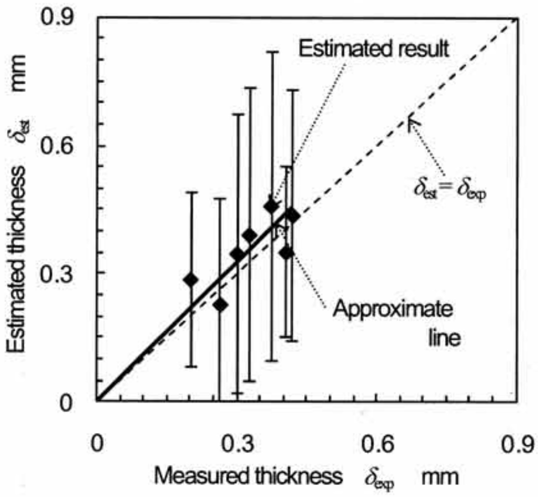

Fig. 3.9 Comparison of the experimental thickness determined by an X-ray diffraction method and estimated thickness determined by the eddy current method

Chapter 4 Evaluation of Stress Anisotropy and Shearing Stress with a Tangential-Rectangular Coil

In this chapter, to establish the evaluating method of stress anisotropy by an eddy current method, a tangential-rectangular coil was used for the stress evaluation. The eddy current made by a tangential-rectangular coil is one-dimension. Firstly, to recognize the character of the tangential-rectangular coil, the variation of eddy current signal with applied stress mechanically induced by a hydraulic jack was investigated. In the next, to make the stress anisotropic state, specimens ground with an angle grinder were prepared. The following abrasives, a depressed center grinding wheel (GW), 3M Scotch-Brite Clean N Strip Bevel Black (CNS), 3M Scotch-Brite Bevel Brown (SB) and TRUSCO GP Top DX # 100 (Flap), were used for abrading or polishing. To reduce the stress anisotropic state, the peened GW specimen that the CP was conducted after grinding with an angle grinder also prepared. The eddy current signals of these specimens were compared. In results, it was revealed that the eddy current signal using the tangential-rectangular coil is affected by the biaxial stress state. The eddy current signal using the coil detects the difference in stress between that in the same direction as the coil winding and that perpendicular to it. In addition, it was revealed that stress anisotropy can be evaluated by the method by varying the coil winding direction. The peening intensity can be evaluated by the eddy current method because peened stress state is equibiaxial compressive stress state. From these results, it seems that the shearing stress can be evaluated by the method. Figure 4.18 shows the relationship between maximum shearing stress and the radius of differential reactance circle which is defined like as Mohr's stress circle. From Fig. 4.18, the maximum shearing stress is related to the radius of differential reactance circle. The direction of the principal stress also can be determined by the method. In addition, the value of the shearing stress seems to be evaluated by the eddy current method combined with an X-ray diffraction method. Merit of combination of the X-ray diffraction method and the eddy current method using the tangential-rectangular coil is that it takes a shorter time to evaluate stress state than the only X-ray diffraction method.

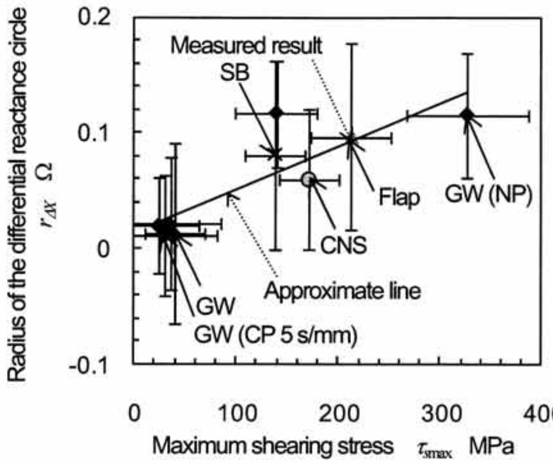

Fig. 4.18 Variation of the radius of the differential reactance circle with the maximum shearing stress

Chapter 5 Conclusions

In the thesis, the stress of cavitation peened SUS316L was evaluated. In this chapter, results of this thesis are summarized, and possibilities of applications to other metallic materials or other processed stainless steels like as shot peening and welding are described. When the eddy current methods use for other materials or processed materials, additional and high-level consideration, experiments and analyses are required to achieve stress evaluation.

This research gives the first success of the possibility of measuring stress state of austenitic stainless steel, SUS316L, used in the industry by an eddy current method. New techniques can be conducted with measuring equipments with lower cost and calculation with a computer and mathematical soft with easier code. The proposed techniques are not only profitable for detecting peening intensity but also become powerful tool for the measurement of anisotropic stress state to prevent SCC or detect the propagating direction of SCC.

論文審査結果の要旨

機器・構造物の寿命や強度を決定する要因である応力腐食割れや疲労強度は、材料表面近傍の応力状態に依存し、また表面加工により応力状態が著しく変化するとともに、残留応力を制御する表面改質によりプラントなどの強度を確保する施工が行われている。したがって、機器・構造物の信頼性を保証して安全に使用するには、表面近傍の応力を非破壊で評価する必要がある。金属材料は、ピエゾ抵抗効果やビラリ効果により電磁気的特性が応力とともに変化するので、電磁気的手法により応力を評価できる可能性があるが、表面改質により導入された等二軸応力を定量的に評価した例はない。本研究では、渦電流の浸透深さが周波数により異なるので渦電流法により表面改質層の厚さの評価が可能であることに着目し、渦電流法による応力の評価手法を提案し、応力腐食割れが問題となっているオーステナイト系ステンレス鋼 **SUS316L** を取り上げ、ステンレス鋼に導入された等二軸応力状態を渦電流法により評価できることを実証するとともに、逆問題解析による表面改質層の深さの同定法を提案して検証し、渦電流法による応力の評価手法の基礎を構築している。本論文は、これらの研究成果をまとめたものであり、全編５章からなる。

第１章は序論であり、本研究の背景、目的および構成を述べている。

第２章では、機械的にステンレス鋼に導入された等二軸応力を、円形コイルを用いて種々の周波数で渦電流法により評価して最適周波数を明らかにしている。この周波数を用いてキャビテーション気泡の崩壊衝撃力を用いて表面改質するキャビテーションピーニングにより付与された圧縮残留応力を渦電流法により評価できることを実証している。これは、工学上有用な成果である。

第３章では、応答曲面法を用いた逆問題解析により電気抵抗率の分布から表面改質層の厚さを同定する方法を提案し、種々の条件でキャビテーションピーニングにより施工したステンレス鋼の表面改質層の厚さを、円形コイルで計測した結果を用いて逆問題解析により同定して検証している。これは、工業的に有益な知見である。

第４章では、表面加工で導入されたせん断応力などの応力状態をかご型コイルによる渦電流法で評価する手法を提案し、研磨加工などの種々の表面加工や表面改質でステンレス鋼に導入された応力状態を評価できることを実証している。これは、工業上有用な成果である。

第５章は結論である。

以上要するに本論文は、渦電流法により表面加工したステンレス鋼の応力状態ならびに厚さを評価できる手法を提案、検証し、ステンレス鋼に表面加工で導入された応力の非破壊評価の基礎を開拓したものであり、ナノメカニクスおよび機械工学の発展に寄与するところが少なくない。

よって、本論文は博士(工学)の学位論文として合格と認める。